USING FREQUENCY ANALYSIS TO DETERMINE WETLAND HYDROPERIOD

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ABSTRACT

Spectral analysis of water-level time series provides invaluable insight into the periodic behavior of hydrological processes. This study analyzes wetland hydroperiod, which is commonly defined as the period of inundation and is thought to be mostly annual, using spectral analysis of observed water-level time series. The results show the water level fluctuation observed in West-Central Florida wetlands follow a predominant semi-annual (180 day) cycle, with water levels fluctuating both above and below land surface.

Keywords- hydrology, time series, frequency analysis, wetlands

1. INTRODUCTION

Wetlands are a significant factor in the health and existence of other natural resources representing unique ecosystems, such as wildlife and water resources including inland lakes, streams, and groundwater. Wetlands are also beneficial to recreation and tourism in Florida. Wetlands occur where surface water collects and/or groundwater interacts with land, inundating the area for extended periods of time (Tiner, 1996). Wetlands generally include swamps, marshes, bogs, and similar areas. The hydrological regime of each wetland differs in frequency, magnitude, timing, and temporal sequences of low and high water (also commonly known as hydroperiod), (Zedler, 2001). For an area to be considered a wetland it must contain water at or near the surface for a period of time (wetland hydrology), wetland plants (hydrophytic vegetation), and periodically anaerobic soils caused by prolonged inundation (hydric soils) (Dennison and Berry, 1993; Tiner, 1996).

Florida's combination of high fire frequency, low topography, high surficial groundwater-tables, and seepage to/from deep groundwater aquifers has produced an unusually diverse array of wetlands (Ewel, 1990). In the past, vegetation was used exclusively in the identification of wetlands and their boundaries. More current approaches, however, take into account vegetation, soil, and hydrologic characteristics for the identification and delineation of wetlands (Tiner, 1996).

The ecological characteristics of a wetland are primarily controlled by the presence and duration of saturated soils or standing water for part of the year (Ewel 1990), known as the hydroperiod. The hydroperiod is the result of the balance between inflows and outflows of water, wetland storage, and the subsurface soil, geology, and groundwater conditions (Mitsch and Gosselink, 2000). Hydroperiod refers to frequency, duration, and depth of the water within the wetland. The periodicity of inundation, permanent, seasonal, or intermittent, is the ecological and functional control for many wetlands. For those wetlands sustained by seepage, subsurface waterlogging or watertable rise, however, it is the periodicity of water-table fluctuations with respect to the root zone that maintains the wetland (Semeniuk and Semeniuk, 1997). Hence, the water budget and the storage capacity of the wetland (above and below ground) ultimately define the hydroperiod.

It is still not known, however, exactly how variations in the hydroperiod of a wetland affect plant and animal communities (Zedler, 2001). Hydroperiod affects soil aeration, which in turn influences the abilty of plants to survive and reproduce. During prolonged inundation, oxygen in the root zone is depleted and concentrations of soluble iron, manganese, and even hydrogen sulfide increase, thereby creating stressful conditions on roots (Ewel, 1990). Only a small portion of the thousands of species of vascular plants on Earth have adapted to survive in waterlogged soils (Mitsch and Gosselink, 2000). Wetlands, therefore, are inhabited by only a particular subset of plant species. Wetlands with longer hydroperiods may, consequently, contain fewer species and serve unique functions.

Wetlands in shallow water table environments such as West-Central Florida are influenced by a shallow and rapidly fluctuating water-table and regular high intensity rainfall events. Yet, depth to the water-table is not typically included as a parameter in the definition of hydroperiod. There is little information regarding the influence of the depth to the water-table in the classification of wetlands. Because wetland ecological condition is controlled not just by the period of inundation, but also by the proximity and depth to the water-table (controlling the dry periods), there is a need to thoroughly define hydroperiod incorporating the depth to water-table.

Spectral analysis of the individual water-level time series data can provide an invaluable insight into the temporal and periodic behavior of hydrological processes (Hegge and Masselink, 1996). For this reason, spectral analysis was used in an attempt to identify dominant frequencies (spectral peaks) in observed water-level time series. Specifically, objectives of this study were to: (1) redefine and quantify wetland "hydroperiod", incorporating both surface and subsurface water-level fluctuations using standard frequency analysis (2) identify predominant hydroperiods of different wetlands, and (3) find the range of the water-level fluctuations associated with predominant hydroperiods.

2. MATERIALS AND METHODOLOGY

2.1 Study Area

The study area chosen is contained within a typical coastal plain environment incorporating part of West-Central Florida located in the Southwest Florida Water Management District (SWFWMD) (Figure 1). The mean annual temperature is 23°C. The long-term average annual precipitation of the region is approximately 1300 mm per year, but precipitation shows substantial spatial and temporal variability (Clayback, 2006; Scott, 2006). On average, the driest months of record are November and April, with the wettest being July and August (NOAA, 2006). The mean annual open-water evaporation rate for the region is 1250 – 1300 mm per year (Clayback, 2006; Ruskauff et al., 2003).

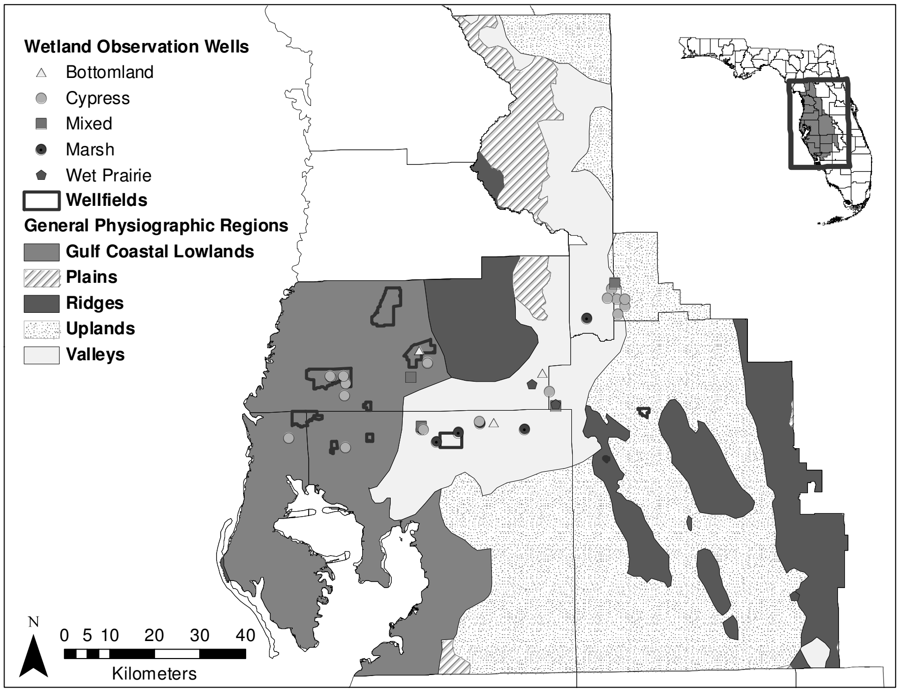

Figure 1. Study Area shown with different physiographic regions and location of wetland observation wells and well fields.

Florida's unique geologic and hydrologic history has produced a sculptured topography. Several distinct physiographic features have been identified in this region (See Figure 1) The physiographic regions of particular interest in this study include (1) the Gulf Coastal Lowlands, (2) the Western Valley, and (3) both the Polk and Lake Uplands. Detailed hydrogeologic information about each of these physiographic regions can be found in Foster (2007) and additional references therein. In summary, each of the physiographic regions differ in terms of average land surface elevation, prominent geologic features as well as depth to the water table below land surface.

2.2 Data

Water-level data used in this study were obtained from thirty-four wells located in the wetlands found in the four described physiographic regions. Eleven of the observation wells are located in the Gulf Coastal Lowlands, two are in the Polk Upland, one well is in the Lake Upland, and the remaining 20 are located in the Western Valley (Figure 1). The types of wetlands that were monitored using these wells include (1) Cypress, (2) Hardwood, (3) Marsh, (4) Wet Prairie, and (5) Stream and Lake Swamps (Figure 1).

Detailed information about each wetland type, their prominent vegetation cover and general hydrologic conditions can be found in Foster (2007). The wells were further classified as well field, which are wells within a well field property boundary, or non-wellfield, which are outside of the well field boundary. This classification was a simplistic attempt to analyze the impact of pumping on wetland water levels in addition to the influence of a particular physiographic region or wetland type. Data collection for the study consisted of two elements, water-level elevation time series and spatial geographic data. All of the data were acquired from SWFWMD and are available at www.swfwmd.state.fl.us. Water-level elevations were recorded in feet above National Geodetic Vertical Datum 1927 (NGVD). The land surface elevation, also in feet above NGVD, was then subtracted from the water elevation data to obtain water-levels with respect to land surface (positive being above land surface and negative below land surface). The amount of data for each well differed from well to well, however, all the selected wells for the analysis had a minimum of two and half years of continuous daily data between January 2000 and November 2006.

2.3 Method

Spectral analysis (Bendat and Piersol, 1986) is widely used to analyze the frequency constituents of time series by numerous scientists from various disciplines (Chatfield, 2004). It has been applied, for example, in investigations of annual temperature variations (Craddock, 1956), ocean waves (Kinsman, 1984), and oscillatory currents (Hardisty, 1993). Spectral analysis can be highly beneficial, as it allows for fine-scale resolution of the range of frequency components. It can be used to de-convolute multiple processes to derive the relative importance of each (e.g. obtain tidal harmonics).

2.3.1 Theory

A brief description of the theory behind spectral analysis is presented here, however, for more detailed information the reader is encourage to refer to texts, such as Box et al. (1994) and Shumway and Stoffer (2006).

2.3.1.1 The Fourier Transformation

The Fourier transform of a discrete time series $x(n)$ with a finite length N, sampled at a uniform sampling frequency f_s, can be expressed as:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-2\pi i k n / N} \qquad k = 0,1,\ldots,N-1 \tag{1}$$

where $X(k)$ is the discrete Fourier series. Redefining Equation 1 in terms of the Fourier cosine $a(k)$ and sine $b(k)$ coefficients yields:

$$X(k) = a(k) - i\,b(k) \qquad k = 0,1,\ldots,N-1 \tag{2}$$

where

$$a(k) = \sum_{n=0}^{N-1} x(n) \cos \frac{2\pi k n}{N} \tag{3}$$

$$b(k) = \sum_{n=0}^{N-1} x(n) \sin \frac{2\pi k n}{N} \tag{4}$$

The length of the time series (N) and the sampling frequency f_s is used to determine the k^{th} Fourier frequency coefficient:

$$f_k = k\, f_s / N \tag{5}$$

The Fourier transform thus enables a time series to be represented by a series of cosines and sines whose frequencies are multiples of f_s / N.

If the data is detrended prior to calculating the discrete Fourier transform, $X(0)$ will be zero. The next element in the discrete Fourier series $X(1)$ is the lowest frequency that can be determined from the time series using Fourier techniques. This frequency is referred to as the fundamental frequency f_f. Similarly, the highest frequency yielding meaningful information from a data set is called the Nyquist frequency (f_c), which is a real number located in the center of the discrete Fourier series $X(N/2)$. All Fourier coefficients beyond the Nyquist frequency are complex conjugates of the first half of the series. These complex conjugates represent negative frequencies, which have no physical meaning and, therefore, do not provide additional information (Hegge and Masselink, 1996; Chatfield, 2004). The Nyquist frequency can be determined directly from the sampling frequency:

$$f_c = f_s / N \tag{6}$$

Unfortunately, aliasing (i.e. the inclusion of the variance of oscillations with frequencies higher than the Nyquist frequency) occurs as a result of excluding complex conjugates from the discrete Fourier series. To minimize the effects of aliasing, a sufficiently small sampling frequency should be used to ensure oscillations greater than half the sampling frequency are reduced (Hegge and Masselink, 1996; Chatfield, 2004).

2.3.1.2 The Periodogram

A periodogram also know as spectra, is a plot of the intensity (i.e. wave energy of a water-level fluctuation) or a multiple of the intensity against frequency for the wave components of a periodic function represented by a Fourier series. After calculating the Fourier coefficients, the periodogram can be computed:

$$P(k) = \frac{a(k)^2 + b(k)^2}{f_s N} \qquad k = 0, \frac{N}{2} \tag{7.1}$$

$$P(k) = \frac{2\left(a(k)^2 + b(k)^2\right)}{f_s N} \qquad k = 1, \dots, \frac{N}{2} - 1 \tag{7.2}$$

Because the Fourier coefficients beyond the Nyquist frequency are complex conjugates, they are not included in the calculation of the periodogram. Instead, the first half of the Fourier coefficients, with the exception of $P(0)$ and $P(N/2)$, are doubled for compensation. $P(k)$ is also referred as the variance-spectral density, power-spectral density, and energy-spectral density (Hegge and Masselink, 1996).

2.3.1.3 Spectral Leakage

Most of the hydrological time series data are of finite length. Distortion of the calculated spectral density function caused by the discontinuities at the two endpoints is referred to as spectral leakage. Spectral leakage causes small amounts of spectral energy to leak into adjacent frequencies, thereby skewing the spectral estimates of respective frequencies.

One of the most popular methods to minimize leakage is the Hann taper method (Hegge and Masselink, 1996; Chatfield, 2004). The application of Hann taper involves multiplying the original time series by the taper $w(n)$:

$$w(n) = 0.5\left(1 - \cos\frac{2\pi n}{N-1}\right) \qquad n = 1,2,\ldots,N \tag{8}$$

Applying a taper prior to calculating the periodogram has been shown to greatly improve the distinction of the power spectral density peaks (Hegge and Masselink, 1996).

2.3.1.4 Spectral Estimates

To improve the reliability (i.e. reduction in variance) of the spectral estimates, different statistical methods can be used. For this particular study, the segment averaging method, proposed by Welch (1967), was used.

The Welch method involves dividing the time series into several small segments with an underlying assumption that the adjacent segments are statistically independent and then calculating periodogram for each segment. The confidence level of the spectral estimates is directly proportional the number of segments used. To obtain a near maximum reduction of variance, a fifty percent overlap between adjacent segments is recommended (Welch, 1967; Hegge and Masselink, 1996)

2.3.2 Application of the Method

MATLAB® and R® were used to perform the aforesaid analysis for all thirty four wells. The time series of the water levels was first linearly detrended. The detrended series was then checked for stationarity using the KPSS (kpss.test) and the augmented Dickey-Fuller test (adf.test) in R. For each of the tests, the linear detrended data had a p value of > 0.05 and < 0.05 respectively (owing to the differences in the null hypothesis of each test), showing that the hypothesis that the series are detrended cannot be rejected. The detrended series were then imported into MATLAB where ‘spectrum.welch’ was used to calculate the spectra for each well with the time series being divided into two segements with a 50% overlap. A Hann Taper window was used to reduce the spectral leakage. A 95% confidence interval on the calculated spectra was also calculated using the following equation

$$\frac{df\ \ P(k)}{\chi^2_{(1-\alpha/2)}} \leq P(k) \leq \frac{df\ \ P(k)}{\chi^2_{\alpha/2}} \tag{9}$$

where *P(k)* is the estimated spectral energy for any kth Fourier coefficient and *df* is the degree of freedoms which for 50% overlap in segments is equal to twice the number of segments (Shumway and Stoffer 2006; Hegge and Masselink 1996). The frequency on the periodograms was converted to time period in days, which was scaled from zero to 365 days, as the objective was to study the fluctuation on an annual basis.

3. RESULTS AND DISCUSSION

A simple plot of the time series allowed for visual identification of trends and illustrated obvious periodicity in the series. This visual inspection is useful in increasing the confidence in the spectral estimates related to each of the Fourier coefficients. From inspection of the hydrographs in Figure 2, it can be observed that one or more predominant seasonal fluctuations are identifiable. In addition, smaller event-driven fluctuations are ubiquitous; however, the event fluctuations occur at a lower magnitude and inconsistent duration (period). Although these wells are located in different physiographic regions as well as distinct types of wetlands, it can be seen that the timing of the minimum and maximum water-levels in the wetlands is consistent. They do, however, differ in relative water depths, as well as in the overall range of the water-level fluctuations. From the observations, there appears to be a winter/spring cycle, which generally occurs from December through May, and a summer/fall cycle that takes place from June through November each year. It is also observed that the range of water-level fluctuation varies both between wetlands and from year to year. Although the magnitude of the water-level varies, its pattern remains consistent.

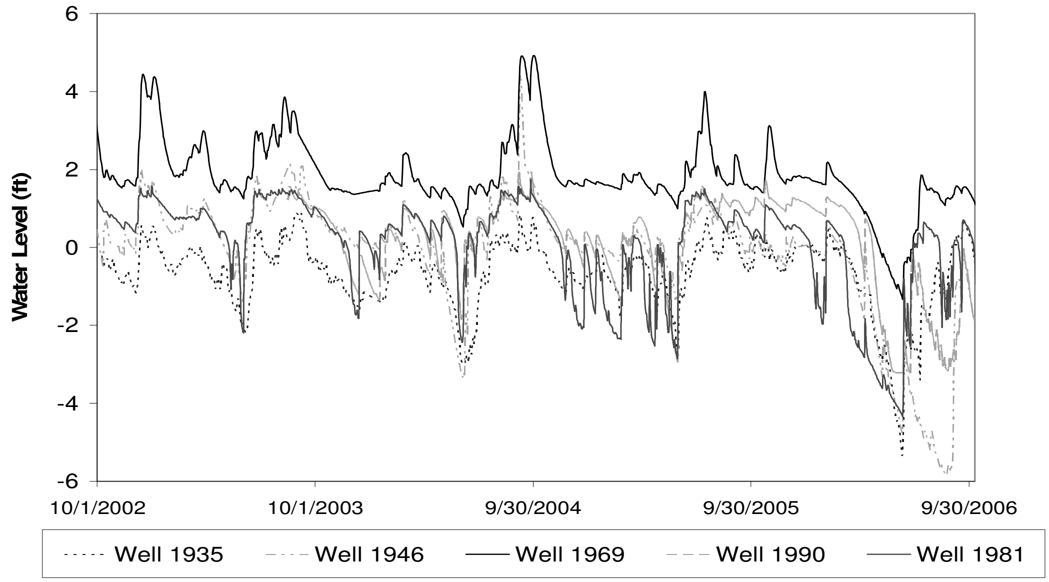

Figure 2. Time series of water levels for wetland wells (a) 1935, a cypress wetland well location in a wellfield in gulf coastal lowland (b) 1946, a mixed wetland forest in gulf coastal lowland (c) 1969, a bottomland well located in western valley (d) 1990, a cypress wetland located in lake upland , and (e) 1981, a wet prairie well located in the western valley.

To further investigate the distinct inter-annual periodicity of water-level fluctuation observed in the time series plots, spectral estimates were plotted for two wells in cypress wetlands found in the gulf coastal lowlands (Figure 3 a and c). Frequency was converted to time period (days) prior to plotting. A distinct spectral peak at approximately 180 days can be observed upon inspection of the plotted spectral analysis graphs. It is useful to plot the preiodogram on log scale, as the confidence interval for spectral estimates becomes a constant value. Figure 3 (b and d) shows the periodogram along with the 95% confidence intervals. The spectral peaks indicate presence of dominant waveforms representative of the temporal component of hydroperiod and encompass the entire range of water-level fluctuations. A pattern of generally decreasing energy with decreasing time period can also be seen. This behavior is typical of natural systems (Hegge and Masselink 1996). It can also be seen from the spectral analysis plots, that for time periods of less than 30 days, spectral energy effectively becomes zero. This justifies that the sampling frequency of 1 day was sufficiently high to minimize the effects of aliasing (Hegge and Masselink 1996). More importantly, it quantifies the obvious observation that storm event water-level fluctuations are much less intense than the dominant summer/fall and winter/spring water-level fluctuation. From all the thirty four well analyzed about 80% of the wells had a primary peak around 180 days (± 10days) and the remaining wells showed a primary annual peak with a secondary peak at 180 days. Figure 4 shows the values of the primary peak obtained from the spectral analysis. A dominant 180 day wave form in the water level observations for all the wetland wells is clearly present.

Hydroperiod as has been traditionally defined as the period for which a wetland remains inundated on an annual basis and is assumed to be constant for a given type of wetland. To test this from the available data period when the water was above the land surface was observed was selected and plotted for each wetland well. Figure 5 shows the plot of the number of days a wetland was inundated and the average depth of inundation. As can be seen from the figure the duration and magnitude of inundation not only varied for different types of wetland but also varied between similar types of wetlands. The variation between similar types of wetland was further enhanced by the presence of a particular well in a well field. For instance, Figure 6 shows the water level variations for the same two wells used in Figure 3 and, although in Figure 3 they both show the dominant 180 days waveform period above land surface, the magnitude of water table fluctuations is highly variable.

The aforesaid discussion clearly points out the inadequacies in the currently used definition of hydroperiod and confirms the need to incorporate water levels both above and below ground and to consider the associated waveform as a more robust method of defining wetland hydroperiod. The spectral analysis of all the available wells show the presence of a 180-day wave form of primary dominance and hence, can be used as the wetland hydroperiod for the wetlands found in west-central Florida.

Further data and analysis is, however, needed to extend this methodology to different environments and wetland types. Future work will include the incorporation of water level fluctuations within the 180 day hydroperiod in an attempt to generalize these fluctuations based on a Fall or Spring hydroperiod (180 days each) and/or based on physiographic regions.

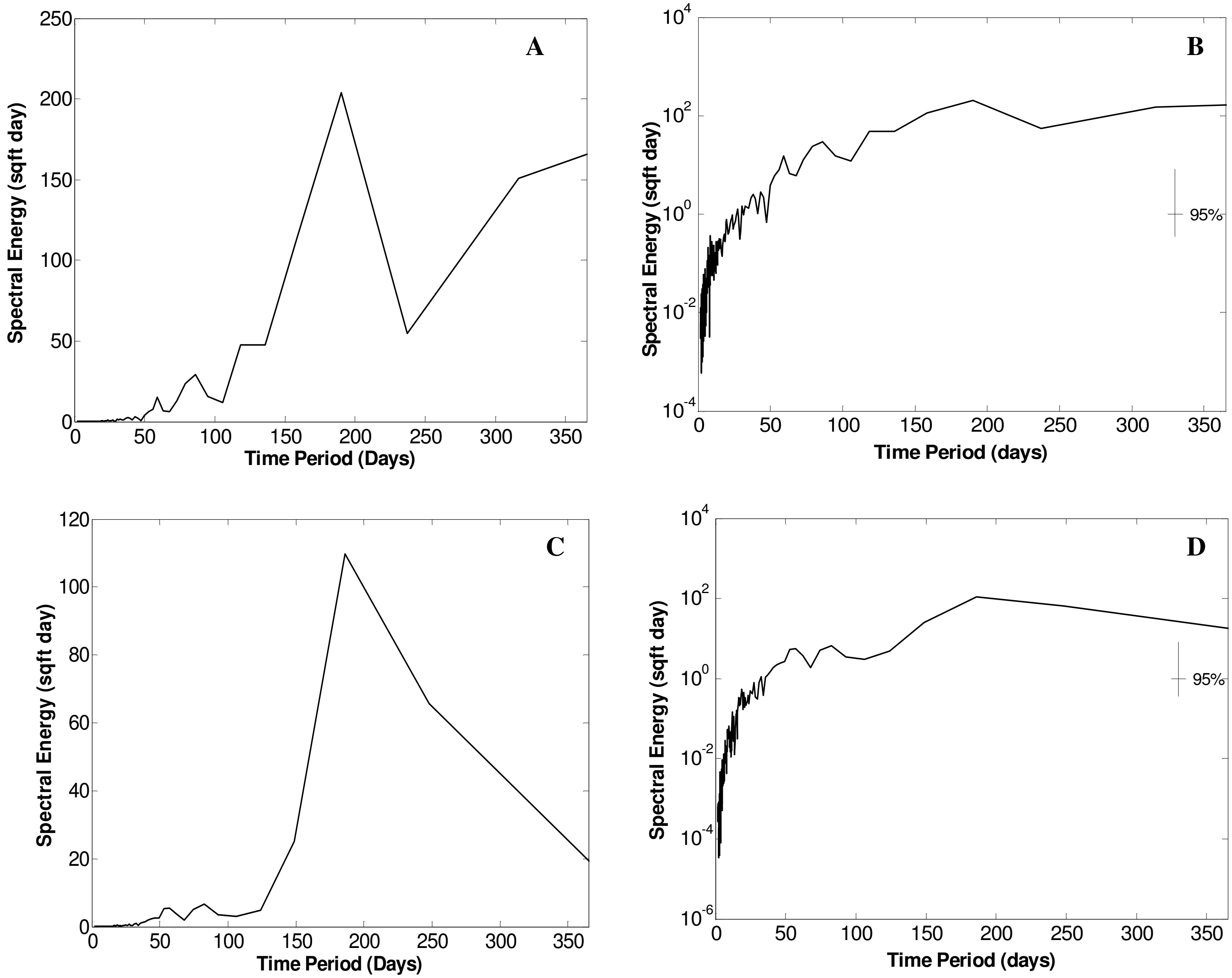

Figure 3. Periodogram on regular and log scale with confidence interval for cypress wetland wells located in gulf coastal lowlands and being (a) and (b) in a well field and (c) and (d) not in a well field.

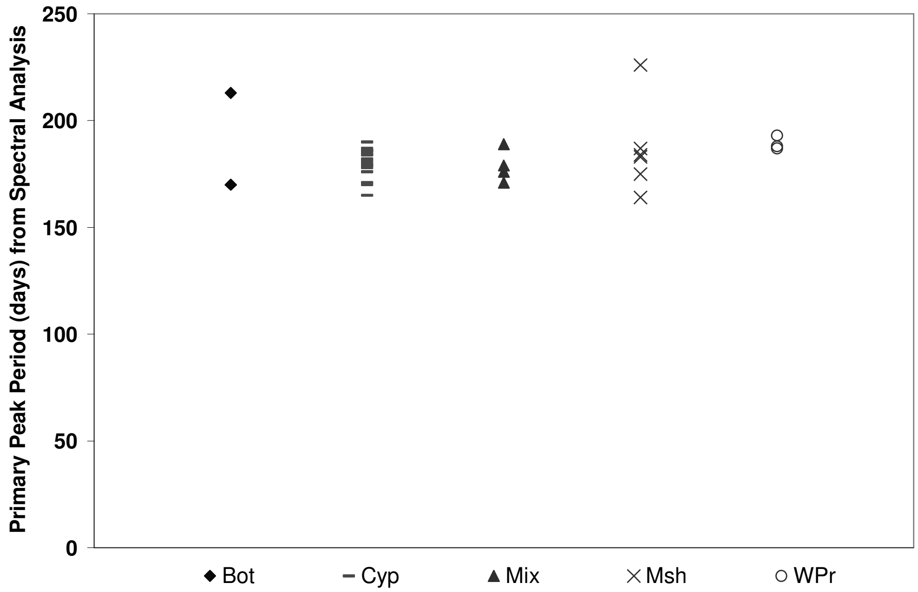

Figure 4. Plot of period of dominant waveform for different types for all the wetlands wells differentiated by the type of wetlands.

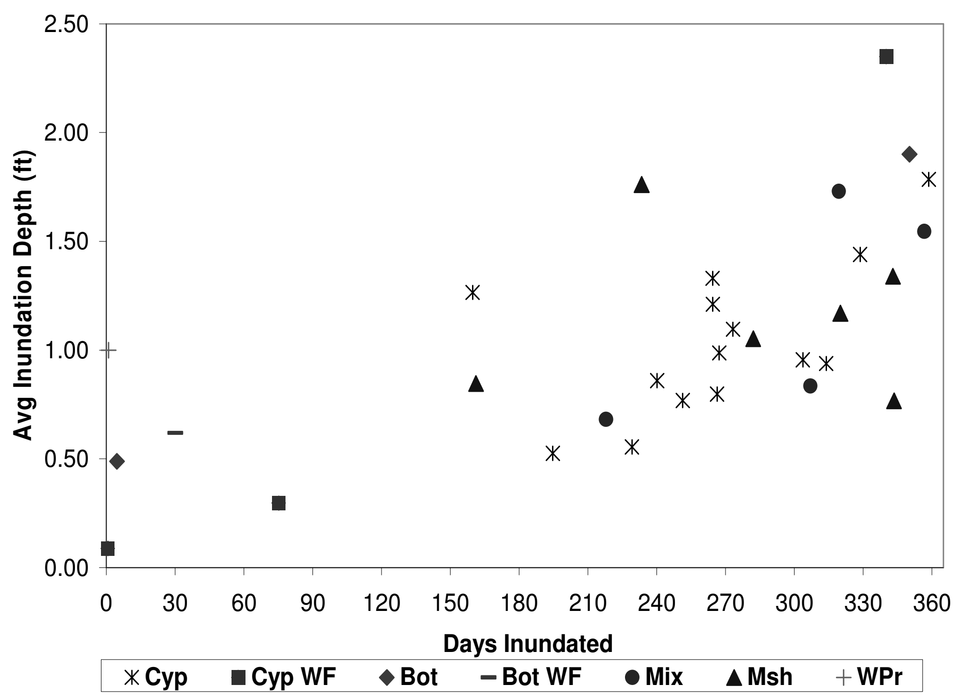

Figure 5. Average period and depth of inundation for all wetland wells.

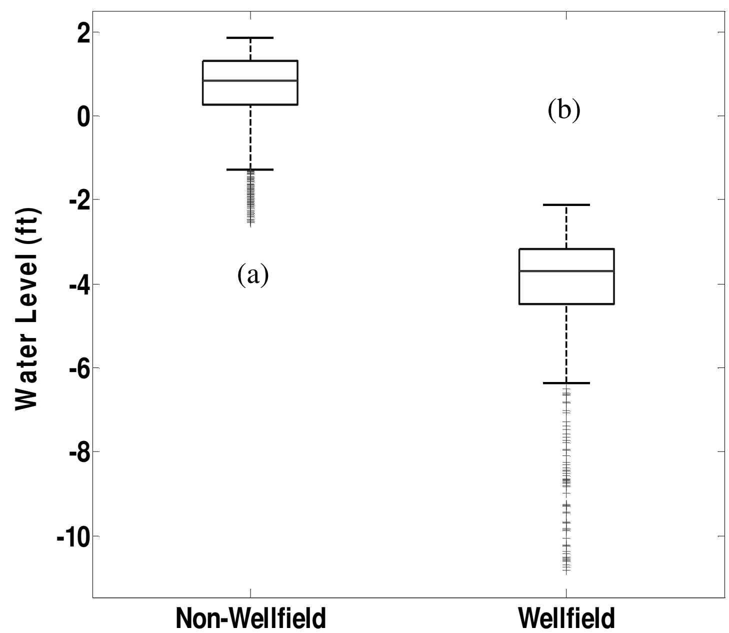

Figure 6. Water level fluctuation of two cypress wells; a) outside a well field and b) in a well field.

4. CONCLUSION

Spectral Analysis of wetland water level data was done to analyze the concept of hydroperiod and compare it with the commonly used hydroperiod definition of the period of inundation. The results clearly indicated a presence of dominant 180 days waveform which controls both above ground and below ground water levels. It is, therefore, logical to abandon the period of inundation approach and define hydroperiod as a wave of water level fluctuations (both above and below ground) with a time period of 180 days. Another interesting result of the analysis, which was observed in all the periodograms, was that, any event with less than 30 days time period, owing to their negligible spectral energy, cannot affect the general water level fluctuation pattern of a wetland. This conclusion is very important from the perspective of modeling water levels in a wetland in response to rainfall runoff events. The analysis is, however, biased by the fact that the wetlands used for the study were local to west-central Florida and, hence, are subjected to similar seasonal variations. The results can, consequently, be successfully used for modeling in west-central Florida. Further analysis with data from different geographical regions will be necessary to determine wetland hydroperiods outside of West-Central Florida.

ACKNOWLEDGEMENTS

The authors like to thank US Army for their funding via US Army research support grant number W911NF-07-1-0283.

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